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The Leidenfrost Maze

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Subjects: Education and Communication

Recent research into applications of the Leidenfrost effect have sparked renewed interest for this phenomenon. We report here on some of these developments, and on their deployment in an undergraduate teaching project that culminated in the production of a viral internet video. We analyse the key ingredients to the project's apparent success, both in terms of physics pedagogy and outreach/public engagement.

Introduction

As part of the BSc degree in Physics at the University of Bath, students undertake a year-long project in their final year, working in pairs, one day a week. The range of projects is extremely diverse, reflecting everything from the core research interests of the academics, to more adventurous and light-hearted ones; some of these projects also explore developments in physics education, outreach and public engagement. In the academic year 2011/12, one of these projects, based on self-propelled Leidenfrost droplets [1] produced results of sufficient quality and quantity to be published in a Nature group journal [2], accompanied by a modest press release from the University's press office. Despite the small scale of the publicity, the project received substantial attention and was covered by various high profile science blogs, internationally [3-5]. However, even before the publication of our paper and the press release, there were signs from the way in which the students were captivated by the physical phenomenon that there was something inherently engaging about this topic. We suspected that beyond its relative accessibility and novelty, its visually striking nature, the sound it makes, the heat that can be felt, the characterful dynamics of the droplets and their controllability all contribute to provide a sensory feast, covering Visual, Auditory and Kinaesthetic (VAK) 'modal preferences for learning' [6], three of the four learning styles of the VARK classification (R standing for Read/write) [7].

This experience, along with video footage and photographic imagery taken during the project, was presented at a meeting of artists and scientists aimed at exploring possible collaborative projects to communicate the fun of science in creative and unconventional ways to diverse audiences¹. This, in turn, led to the proposal of an experimental undergraduate project in which the students would rely on "the beauty of water" to present some novel cutting-edge physics and spread the excitement of scientific research. The pedagogic value of this project relied on the following three motivations. First, STEM (Science, Technology, Engineering and Maths) undergraduate degrees are very much enriched when course contents and student tasks are built around and informed by scientific research, and especially by current hot topics [14-17]. Secondly, communicating complex physics to wide ranging audiences places students in either contact with or in the role of the 'more knowledgeable other' (MKO), inducing them to negotiate meaning and representations of physics concepts in a continuous exploration and redefinition of their zone of proximal development (ZPD) [18, 19]. When demonstrating at fairs and public

events, students would have to explain and enthuse children of all ages but also their parents, often helping scaffolding the conversation between a parent and a child in a dynamic three way conversation where the role of 'more knowledgeable other' could be frequently changing. When presenting at school careers fairs or University UCAS and Open days, students would be often required to go much more in depth about the physics involved. Thirdly, giving students free rein to explore means and media for effective communication, including cross-disciplinary and multiplatform technology approaches, allowed full deployment of their autonomy and creativity; this would in turn stimulate critical decision making throughout the learning process, consolidating some of those transferrable skills and generic graduate attributes that define independent life-long learners [20-23].

Background Physics: Self-propelled Leidenfrost Droplets

The Leidenfrost effect is a phenomenon in which a droplet of liquid, on a surface which is much hotter than the liquid's boiling point, will levitate above a cushion of its own vapour. Although it has been known about for a long time [24, 25], complexities that arise due to interactions between three phases of matter far from equilibrium have kept exploratory and investigative efforts from being far from exhaustive or comprehensive. However, It has recently attracted renewed scientific interest [26] due to a range of factors. On one hand, technological advancements such as in high speed imaging, nanotechnology and computational fluid dynamics are enabling its complexities to be examined in new ways. On the other, developments in microfluidics and heat management call for a deeper understanding of the surrounding phenomena. Recent examples of research into the Leidenfrost effect range from its use in the chemical synthesis of nano-particles [27] to the behaviour of boiling on super-hydrophobic surfaces [28].

Here, we focus on the self-propulsion of Leidenfrost droplets on surfaces prepared with a periodic but asymmetric sawtooth topography, which was first documented by Linke et al in 2006 [1]. An example of a sawtooth surface is shown in Figure 1(c). While there remain some uncertainties about the rich phenomenology associated with this effect, and an ongoing debate concerning the basic mechanism behind the propulsion, a good working intuitive picture is that the asymmetry of the teeth leads to an asymmetry in the flow of gas beneath the droplet on which the droplet sits, which in turn leads to a net lateral force on the droplet through viscous

drag [29, 30]. This also implies that the same propulsion is possible for sublimating solids on such sawtoothed surfaces, and indeed, there is a magnificent demonstration of this in reference [31].

In the initial project of 2011/12 [2], the set objectives were to recreate this effect in our laboratory and then to explore any aspect of the physics or technology the students wanted to, provided the work was original. This led them to focus on the question “how steep an incline can the droplets climb?”, perhaps a question which arises through natural curiosity, as opposed to approaches such as testing predictions extrapolated from existing published models that might be favored in more traditional settings. The findings of this pursuit, in turn, led the students to record and analyse the sound produced by the droplets which turns out to contain information from which to gain further physical insight [2]. At the same time, results were obtained that raised further questions involving how the droplets look and how we can visualise various physical aspects (V), the sounds produced by the droplets (A) and how we can control and use the droplets (K). These produced a fertile basis on which to run further student projects, one of which is the outreach project which we describe in this paper.

The Outreach Project and the Demonstration Piece: The Leidenfrost Maze

The setting for the outreach project was another final year project, run during the academic year 2012/13; the brief was very simple: design, build and then test a demonstration piece, to be used at STEM (Science, Technology, Engineering and Mathematics) outreach events. Only one constraint was placed: that the subject matter of the demonstration should involve water in some way. The project supervisors agreed that water somehow had an intrinsic engagement value, due, beyond our experiences with the Leidenfrost effect, to it being ubiquitous and essential to our lives but at the same time elusive in its detailed properties as a substance [32]; its apparent visual simplicity linked to its ability to generate remarkable dynamic patterns and effects perhaps being at the heart of the aesthetic and emotive appeal that many water based ornamental artefacts indeed possess [33].

At the University of Bath, public outreach is part of both undergraduate and postgraduate education and indeed, it is formally included in the undergraduate curriculum which contains a portfolio based unit on Communicating Physics. The setting of the Final Year Project was

chosen, however, as it enabled greater focus, flexibility and freedom for the students to experiment and develop the physics and technology for the demonstration. This choice also enabled the students to be based in a research laboratory at which the physics of self-propelled Leidenfrost droplets were being investigated by their peers, allowing them to interact and exchange ideas, benefitting mutually through peer learning. Naturally, in this environment, the idea that was instantly proposed and immediately climbed to the top of the list of possible directions, was to make something fun using self-propelled Leidenfrost droplets.

After some energetic discussion between the students, the demonstration piece was designed to be a reconfigurable “maze”, or a track along which droplets would follow a predetermined path [Fig. 1]. The maze consisted of an aluminium box into which a 7 by 7 array of blocks could be arranged. The blocks were 30 mm x 30 mm squares, 13 mm thick, with the exposed surface either prepared smooth, or with a sawtooth topography: the sawtoothed surfaces propel droplets in a fixed direction, while the smooth surfaces allow droplets to drift across. Rectangular sheets, 25 mm wide, 1 mm thick of various lengths that are multiples of 30 mm were prepared to be insertable, to act as walls off which the droplets can bounce. 13 mm wide sheets were also prepared, to act as spacers to lie between the blocks so that the dimensions of the rows and columns remained commensurate when the walls were put into place. A simple mechanism consisting of thick aluminium sheets and sets of hex-key pushers allowed the blocks, walls and spacers to be pushed into alignment [Fig. 1(d)].

The maze is operated by placing it on a hotplate, keeping the temperature at the surface to be in the range 240 - 270 °C, and then simply dropping droplets of distilled water onto the maze. A couple of additional blocks of different design were also prepared: one which consisted of a bowl machined out from the surface so that it would form a gravitational potential well for the droplets, and one which had a length equivalent to three square blocks, with an inclined surface whose surface was prepared to drive droplets uphill [Fig. 1(a)]. These blocks could be inserted into the maze to form part of the track, or could be used stand-alone on a separate hotplate².

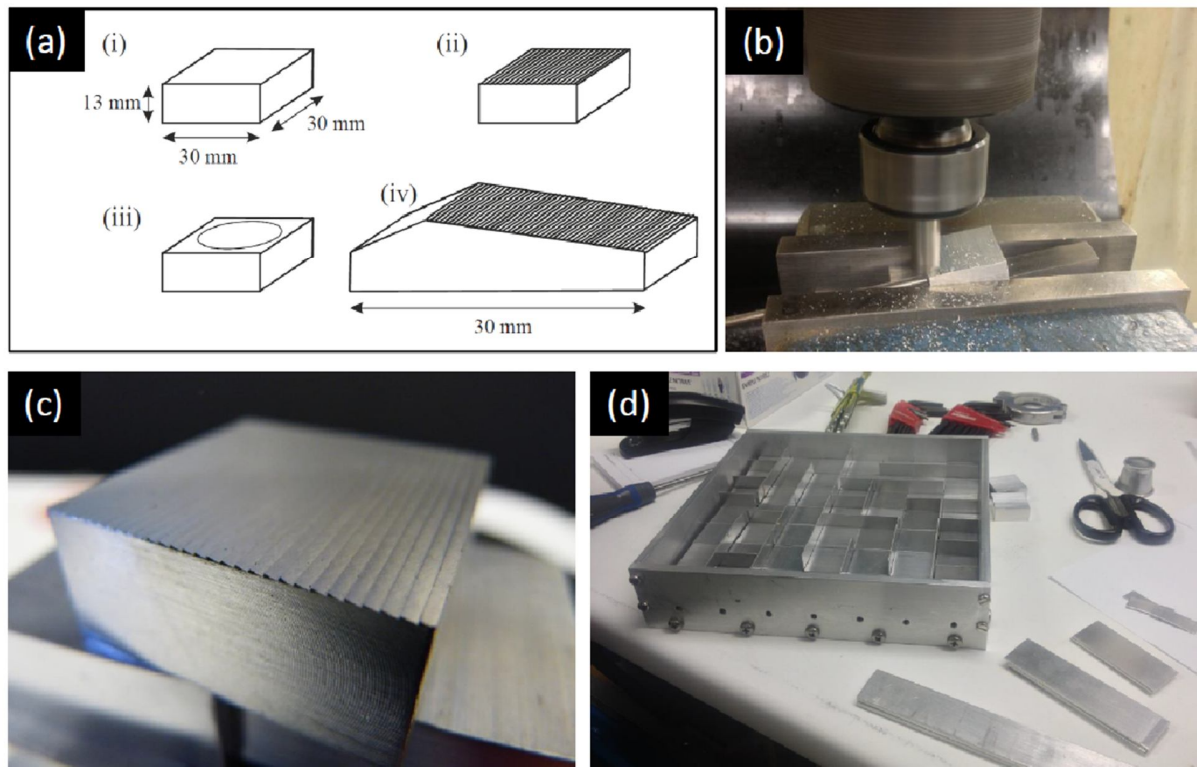


Figure 1: Design and construction of the Leidenfrost Maze. (a) Schematics of the blocks – not to scale. (i) A plain block with a plain surface. (ii) A block with sawtooth surface. (iii) A block with a bowl. (iv) A block with an inclined surface. (b) Photograph of the surface texture being milled. (c) A finished block with a saw-teeth-textured surface. (d) The completed Leidenfrost Maze.

Using the Leidenfrost Maze

The maze was trialled in different contexts with a range of audiences: at University open days, targeting sixth-formers and their parents, at options evenings in local schools with GCSE students (General Certificate of Secondary Education - typically 2-year courses undertaken by students in the UK between ages 14-16), at local science fairs aimed at children aged 9 and above. Clearly, our objectives at each of these events were different, and the maze had to be presented differently. However, at any of these events, and no matter who the target audience was, we wanted to communicate as much enthusiasm, fun and science as possible.

A demonstration would usually use a portable double electrical hob, with one hob for the maze, and the second hob used to demonstrate various other aspects of the Leidenfrost effect, such as for introducing the basics. Nucleate boiling (in which bubbles form and is the form of boiling most people are familiar with) [24, 25] can be demonstrated by placing a fresh room temperature piece of metal on the second hob, and then as the piece heats up, an explanation can be given as the boiling changes to transition boiling (violent and turbulent evaporation) and then film boiling of the Leidenfrost effect (a relatively slow, quiet and smooth evaporation process). At this point, showing Leidenfrost drops vibrate [34] in a small smooth bowl displaying standing waves around the rim arouses quite a bit of buzz in the audience and it seems that many find this pretty. The fact that the Leidenfrost temperature can be changed by changing the surface quality [35, 36] can be demonstrated too, for instance by preparing an otherwise identical bowl with a rough surface. The relevance of this to applications in cooling is fairly straightforward and is an effective way of linking the science to serious real-life technology. There are also rich examples of recent research surrounding the Leidenfrost effect as already described [26] that can be invoked to highlight its topicality.

The sound made by the droplets, their visual properties and the way they move can also be exploited in an effort to captivate the audience - methods for attracting attention to their details include highlighting how the seeming opacity of the droplets change with temperature or surface texture, or holding a droplet on a slope using a pipette and describing how the shape the droplets take reveal the dynamics of the water within the droplet.

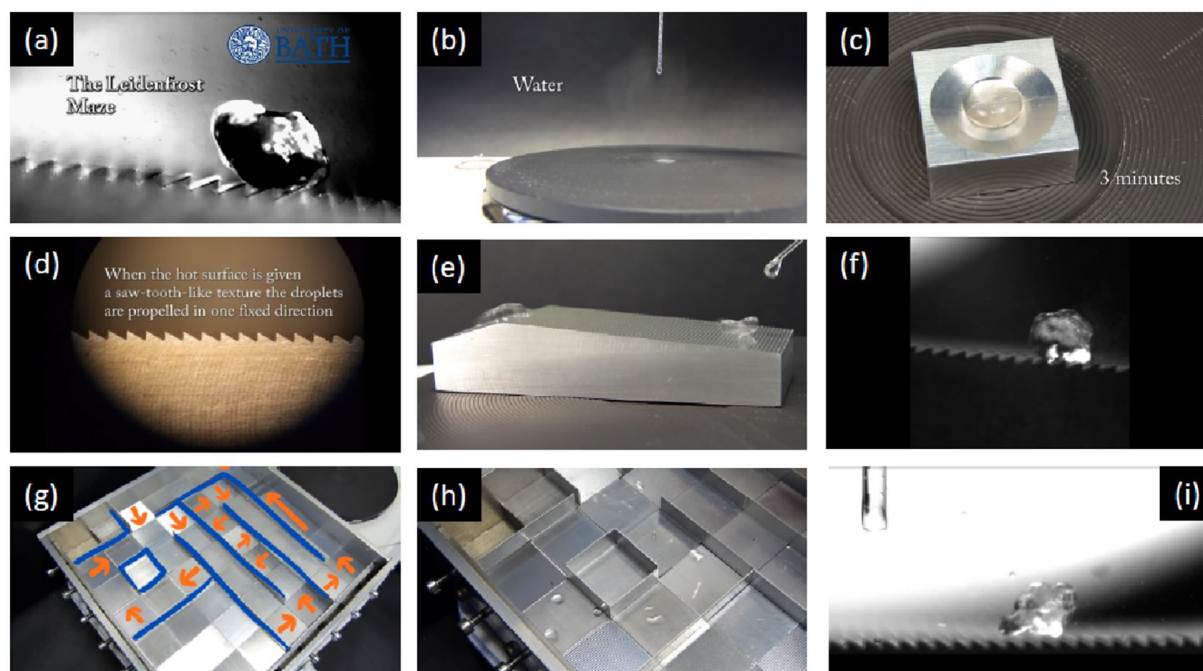


Figure 2: The viral video. (a) Thumbnail and title page. (b) – (d) A short and simple introduction to the basic phenomenology. (e) Demonstration of uphill propulsion. (f) Slow motion footage of uphill propulsion. (g) Introduction to the maze. (h) Close-up of droplet motion. (i) More slow-motion footage.

The Video

Beyond the inherent learning value of this activity for the students in developing a range of transferable skills [20-23], the production of a video had a two-sided aim. On one hand, we wanted a film that could be used at the events, in conjunction with the demonstration to show high-speed video footage to help explain the physics and highlight certain technicalities. On the other hand, we wanted a video that was sufficiently self-contained, so that it could, firstly, be viewed when the physical maze is not being manned, and secondly, the video in itself could potentially act as an independent outreach resource such as for use by other science communicators. These aims may, at first sight, seem conflicting but in hindsight, they may have provided just the right balance to attract attention on the internet.

Our chosen mode of release was to upload the video onto a channel belonging to the University

on an open access video hosting site (YouTube), accompanied by a low-key press-item. The press officers who are gate-keepers to what appears on these channels served as excellent quality control to the video production. The students wanted to pack the video full of science, full of images and full of explanations. Press staff want quick punchy action.

Once again, we made it a principle for the academics to be involved as little as possible in the actual content of the video - what footage to take and include, and the style of the video [20-23]. The latter is likely a crucial point in order to create something that has aesthetic resonance with the generation of people we want to address, and the people that are most likely to spread the video once published. Limited academic guidance was provided to interpret feedback from the press-office and to help decide what can be left out to create something short while retaining its information value.

Screenshots from the final 3 minute video are shown in Figure 2. The thumbnail, which is also the first 4 seconds of the video announcing the title, shows a high speed, black and white photograph of a droplet of water, climbing up an incline [Fig. 2(a)]. The first screen is followed by a rather long (50 seconds) introduction to the Leidenfrost effect itself [Fig. 2(b),(c)] which begins with water just dripping onto a hotplate, something which most people can relate to from everyday experience. There were concerns that this was far too long - that most viewers wouldn't want to wait so long before being shown something new. This, however, was decided to be acceptable on the basis that the opening title page had a sufficiently striking image of what is to come (viewer retention statistics are presented in the Supplementary Information). This is then followed by a single sentence being shown [Fig.2(d)] to describe a key aspect of the Leidenfrost effect, followed by a clip showing droplets climbing uphill [Fig. 2(e)] and high-speed-camera footage [Fig. 2(f)]. The Leidenfrost Maze is introduced at this point with a minimal diagram hinting at what it does [Fig. 2(g)] after which follows 80 seconds of footage of the droplets racing through the maze and slow-motion videos [Fig. 2(h),(i)]. The concluding sequence returns to water dripping on a hotplate, to remind the viewer that what they have just seen is just water on hot surfaces.

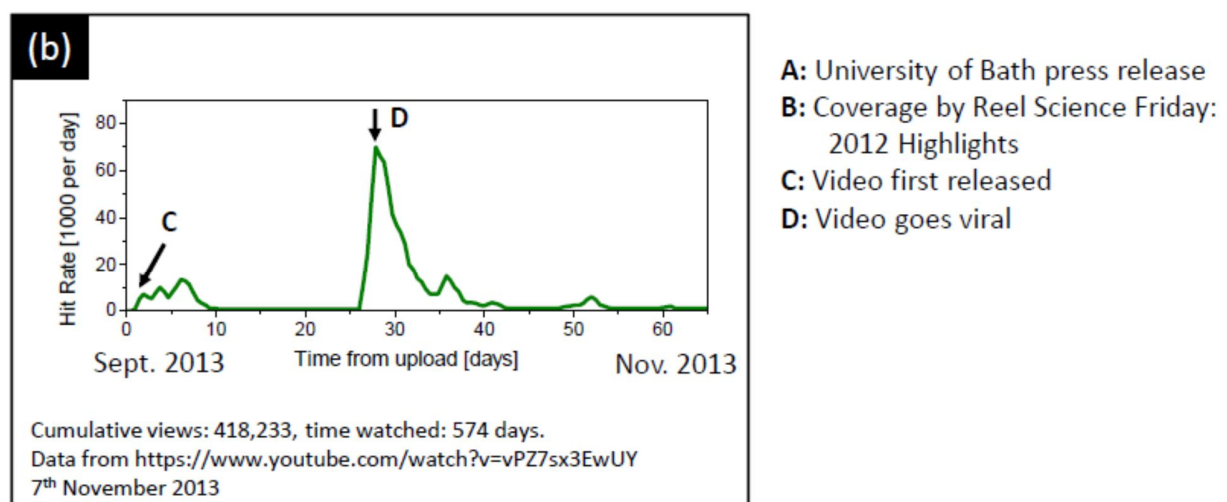
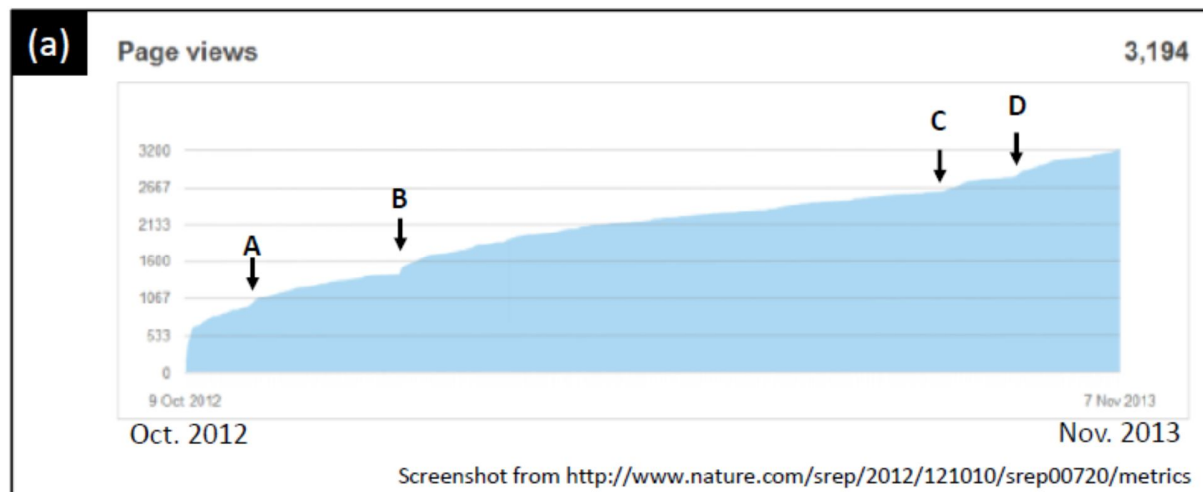


Figure 3: Instant metrics. (a) Cumulative page views of reference [2] from the publisher's website. The figure embeds a screenshot from [37], Scientific Reports, Nature Publishing Group. (b) Daily hit rate of the video hosted on YouTube [38]. The data was extracted from a graphical representation and then re-plotted.

Examples of the reception the video has had can be seen readily by simply performing internet searches for "Leidenfrost maze" which return many blogs, news websites, tweets and other social media pages across which the video has been shared and discussed. Most discussions on very popular sites, in the form of "comments", tend to be somewhat superficial, but some reveal debates that are quite involved. It is clear to see that many have investigated the

Leidenfrost effect on resources such as Wikipedia as figures and text from it appear in their blogs.

As a crude, short-term but immediate demonstration of the impact it has had, we find that structure can be seen on metrics data on our 2012 paper on the Leidenfrost effect [2] correlating with view-rates on the video. The number of times the paper has been viewed is shown in Figure 3(a) [37]. Similar data for the video hosted on YouTube is displayed in Figure 3(b) [38], showing two peaks; the one in October 2013 [feature D in 3(b)] being much stronger than the initial peak in the previous month [feature C in 3(b)]. While the two sets of data correlate in timing, the page views for the paper have similar sized features [C and D in Figure 3(a)] corresponding to these two events. The relative size of the two features suggests that the initial surge on YouTube views had a higher proportion of active, information-hungry viewers who were interested in finding out more, compared to the second surge with a much greater but presumably more diverse audience.

Correlating structure can also be seen in the statistics of the use of the word “Leidenfrost” on a major search engine (data not shown). The video has also attracted attention from media organisations internationally, and we continue to receive enquiries more than ten months after the initial release of the original video. The maze and the video have definitely been successful in drawing attention to self-propelled Leidenfrost droplets and as devices for communicating science. Further statistics from YouTube are described in the Supplementary Information.

Feedback and Reflections

Harvesting discussions and comments on the internet provide feedback that is often different from feedback obtained through direct conversations with individuals or questionnaires after shows or talks at outreach events. The latter are directed at “us” and besides the questions directly posed to them, the audience usually only tell us what they consider to be things that we would want to know. In contrast, comments and discussions on the internet are things communicated between members of the audience and different aspects of their reaction are expressed. Some comments are akin to what people might say to someone watching television with you in the same room. One type of comment on the internet, never heard by us expressed at outreach events, were comments personifying the droplets of water. Comments such as “I

feel sorry for the poor droplets”, “I can almost hear the droplets go “Ouch, ouch, hot, hot, ouch!””, were common. Some viewers expressed that they found the droplets cute. It is evident that these images do much more than convey details of the physical phenomena and are evoking emotional responses, highlighting the importance of aesthetic and emotive qualities of these stimuli. The title given by the producers of *El Hormiguero*, a Spanish TV programme where the maze featured, seems most fitting in this context: “Las gotas de agua cobran vida” (“water droplets come alive”).

This leads us to a key ingredient which we feel was crucial to the project. This is to allow the students as much freedom as possible in the creative process. There were many instances where interventions by the academic supervisors were deliberately held back. At the initial stages, when deciding what demonstrations to make, one of the supervisors’ view was that a maze is somewhat too gimmicky. At the design stage, the dimensions of the maze, the way in which bolts protruded from the sides etc. seemed clumsy and unpolished. When footage was being chosen for the video, some high-speed photography chosen had technical faults, in terms of lighting and focus etc. from the researcher’s point-of-view when considered as images for extracting scientific data. The net result of this, however, was a demonstration piece and a video that are full of character and spirit.

An obvious but noteworthy ingredient is the combination of accessibility with novelty. Based on feedback obtained through live demonstration events, whilst, to our surprise, many people were unfamiliar with the basic Leidenfrost effect, people were often familiar with what happens with water on a frying pan and that this is also a traditional technique for gauging how hot a pan is in cooking. Further, absolutely everyone seemed to be familiar with boiling water. Indeed, the accessibility of Leidenfrost phenomena has previously been exploited in school-level pedagogical contexts and has been documented on numerous occasions [39-41]. In contrast, everyone expressed surprise at self-propelled droplets navigating a maze and climbing slopes. To most, the idea that anything goes upwards instead of downwards seems to be counterintuitive. Even for people with technical backgrounds, the idea that the droplets travel in the opposite direction to what would be expected of a dissipative ball being randomly jiggled is counterintuitive. These demonstrations seemed to intrigue everyone ranging from professional engineer parents of prospective undergraduates to school children. The novelty is ensured by choosing a phenomenon that has only recently been documented. In this case, the self-propulsion was only first reported in 2006 [1]. We knew that it was engaging to final year

undergraduates from our experience with doing a research project [2], and this guaranteed that the project students working on the outreach project would choose this phenomenon and engage with it as well.

Finally, for the students who undertook the outreach project, this activity has enabled them to interact with the supervisors on outward-facing work, which is an activity often limited to postgraduate study. They have also interacted with students investigating the science, the press-office as well as the audiences and facilitators of outreach events, becoming very much partners in the primary University enterprise of creating and communicating scientific knowledge. Above all perhaps, the students had the opportunity to engage in all aspects of a multifaceted project and were given the opportunity to be in control, to say “I did this myself”, a key aspect of long lasting transformative learning [42]. The buzz generated by the media attention also provides excitement for other students in the Department and serves to create a positive atmosphere and helps to develop a culture in which having fun is seen to be productive and rewarding.

Summary

We conclude by listing the key ingredients which we feel were essential to the usefulness and enjoyment of our experiences with the Leidenfrost Maze. 1) Take science that is relatively new. 2) Let the students choose how it is fun, interesting, stimulating or impressive. 3) Let the students dictate the aesthetics. 4) Listen to the press-office. 5) Have fun!

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Footnotes

¹ On 24th September 2012 a group of artists, art curators and academics met at the University of Bath for a workshop titled *The Impact of Art and Science*. By looking at scientific output of aesthetic significance (see, as an example, Professor sir Michael Berry's work [8]), and at examples of artists inspired by science (Frederique Swist [9], Peter Randall-Page [10] and Gabriele Gelatti [11] just to mention a few), the participants presented their own work and discussed possible collaborations. Possible sources of funding were also discussed. For example, the Wellcome Trust extensively funds education and public engagement projects involving scientists and artists [12, 13].

² At a very practical level, a few points are worth highlighting. Firstly, blocks of metal heated to a high temperature possess a lot of heat, and so it can take quite some time not only to heat up to the right temperature, but also to cool down after use. We would therefore recommend that the blocks and the case should be made less bulky than our original design. Secondly, the propulsion becomes weaker if the temperature becomes too high (for our blocks, above about 270 °C), at which point droplets will no longer climb uphill very well, and parts of the maze will not operate if there is the slightest of inclines. Once again, the maze can take a considerable length of time to cool back down if it is overheated too much. Thirdly, as another consequence of the blocks possessing a lot of heat, if they are accidentally dropped onto an electrical cable, they can melt through the insulation like a hot knife through butter and can be an electrical and fire hazard.

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Supplementary Information - Statistics

In this Supplementary Information, we present statistics on the main upload of the original video that were available to us through YouTube along with brief descriptions and comments. While there are clear limits to what can be inferred from these, they do provide insights into who has watched the video, how the viewers came to find the video and how the video was received.

Demographic Data

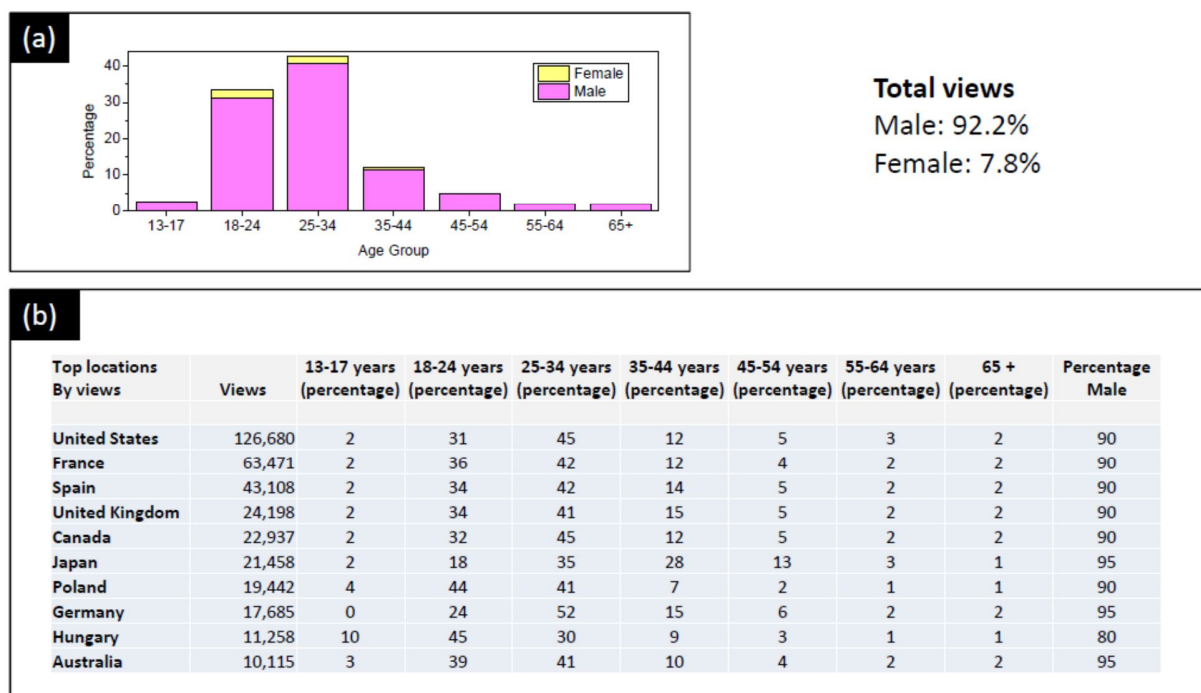


Figure S1. Demographic data of the video hosted on YouTube. Data harvested from youtube.com on 29th July 2014. (a) The bar-chart shows the percentage of total views per age-group. (Data was extracted from a graphical representation and then re-plotted.) (b) The table shows a breakdown according to location. Data on gender on the far-right column was extracted from a graphical representation.

Demographic data is presented in Figure S1, which breaks down the proportion of viewers according to age group and gender. The exact extent to which these figures reflect who actually physically watched the video is questionable, but there are two extremely strong messages that

cannot be denied. The first message is that the viewers are overwhelmingly male with less than 8% of the viewers being female. This male domination of the viewership seems also to be consistent within the top 10 viewing countries. The second conclusion that can be drawn is that the largest viewership comes from the age groups 18-24 and 25-34 with a combined percentage of over 70%. This is in stark contrast to the age-group 13-17 accounting for only a few percent. The fraction of viewers older than 35 is also small, indicating that 13-17 year-olds viewing the video on their parent's accounts must also remain a small fraction. In this respect, the video has mainly hit an audience of young men that was not originally targeted.

Traffic Data

Traffic Source	Views	Percentage
Unknown - embedded player	334,909	69.0
External website	76,552	16.0
Unknown - direct	57,189	12.0
YouTube search	10,016	2.1
YouTube suggested video	2,994	0.6
YouTube guide	1,939	0.4
YouTube playlist	1,068	0.2
YouTube channel page	433	0.1
YouTube - other features	426	0.1
Google search	183	0.0
External app	170	0.0
YouTube advertising	2	0.0

Figure S2. Traffic data. Harvested from youtube.com on 29th July 2014.

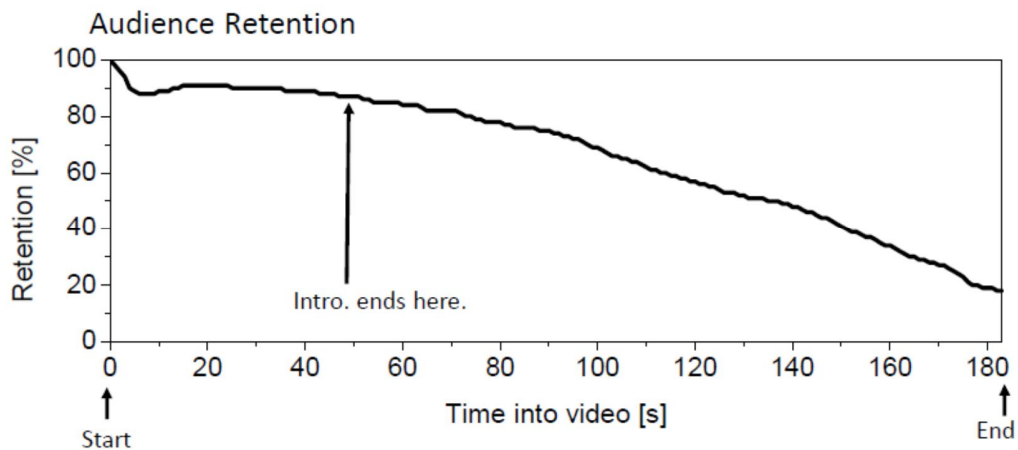


Figure S3. Audience retention. Data harvested from youtube.com on 29th July 2014 (numerical data extracted from graphical representation and then re-plotted). The average view duration was 1 min. 59 seconds (65%).

Traffic source data provide insights as to how the video was propagated. Figure S2 shows the breakdown on views according to how the video was reached. It reveals that by far the most common means was through embedded videos. These are videos embedded in news or magazine sites or blogs. In contrast, viewers who reached it via YouTube, such as through their suggestion system, make up a tiny fraction of the viewership. It demonstrates the power of having the video hosted on a site on which the video is embeddable, even if the channel on the site has close-to-zero subscribers.

Audience retention data [Figure S3] provides feedback on the behaviour of the viewers while the video is replayed. The initial drop of about 10% is presumably due to people stopping the video after an accidental click, an unwanted automatic start or a start in a continuous playlist which is then skipped. There are also options for starting a video at a certain time into it, which may account for a slight increase. This is followed by a plateau which lasts to about 50 seconds into the video, which corresponds to the introductory section describing the basics of the Leidenfrost effect. Retention then begins to drop, as the sequence showing footage of droplets self-propelling begins. This confirms our assumption when making the film, that viewers are prepared to wait 50 seconds to find out what it is about. Retention then slowly decays as the viewers decide that they have seen enough.